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Quantifying the Effect of Coronagraphs on Planet Photometry with the James Webb Space Telescope

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Abstract

The launch of the James Webb Space Telescope (JWST) in 2021 will revolutionize exoplanetary science by providing detailed characterizations of exoplanets within the infrared range of 3–13 microns. This is of particular interest to the field of direct imaging, where empirical models that remove excess starlight from imaged extrasolar systems have proven vital to the discovery of exoplanets. pyKLIP is one of the most modern python libraries with such capabilities, allowing its users to reveal exoplanets hidden behind the starlight. However, the pyKLIP algorithms are not presently able to handle coronagraph usage with the incoming JWST data. In preparation for the launch of this telescope, we upgraded pyKLIPs ability to correct for a coronagraph's effect on the throughput of off-axis sources when determining photometry. Given the coronagraph's transmission profile, pyKLIP v2.2 is now able to successfully account for each of NIRCam's five coronagraphs.

1. Introduction

Over the past decade, high contrast imaging has led to the discovery of more than 50 new exoplanets, many of which have probed planet–star separations of up to 1000 au (Bowler 2016). This exoplanet detection technique involves capturing images of planets orbiting their host stars, which allows us to spatially separate the colors and spectra of exoplanets from that of their host stars. In modern astronomy's endeavor to identify new habitable worlds, such spectral information has proven vital to our understanding of the mysterious compositions of exoplanet atmospheres.

The much anticipated launch of the James Webb Space Telescope (JWST) in 2021 will expand the capabilities of imaging. Within the infrared 3–13 micron range that this telescope covers, exoplanet spectral features are at their brightest, enabling more detailed characterizations of their atmospheres. To detect these planets, JWST offers the use of coronagraphs to improve imaging performance by physically blocking starlight, enabling us to more easily see underlying planets. In addition to blocking starlight, coronagraphs can also suppress some light from an off-axis source like a planet. These instruments block different amounts of planet light at different distances from the star, allowing nearly 0% of light through at the center of the coronagraph, and 100% through at the edges of the image, while light transmission in between varies. While coronagraphs can certainly be advantageous in reducing the planet–star contrast, it also means that any planet orbiting close to its host star might suffer the dimming effects of a coronagraph. JWST'S Near Infrared Camera (NIRCam) uses 5 different coronagraphs, each of which has a different transmission profile. This means that the same planet may be imaged quite differently depending on the coronagraph in use. Therefore, we must account for the effect each coronagraph can have on our ability to retrieve reliable photometric measurements.

In preparation for JWST, we have commenced the restructuring of relevant software to be able to handle the use of its coronagraphs with incoming data. Specifically,we have focused our efforts on the python library `pyKLIP`. `pyKLIP` allows astronomers to process imaged data by fitting and removing starlight (Wang et al. 2015). Given a set of images of an extrasolar system, it uses the Karhunen-Loeve Image Processing (KLIP) algorithm to find patterns within each image and build a model of the star (Soummer et al. 2012). The algorithm then subtracts that bright starlight from images, revealing exoplanets that were lying underneath the stellar glare. Once exoplanets have been found in the data, `pyKLIP` can estimate their positions and fluxes. A failure to account for the use of a coronagraph at this stage could lead to misleading planet photometric measurements that vary based on the filter and coronagraph in use. Therefore, we developed a mechanism for incorporating coronagraphic transmission when estimating planet flux with `pyKLIP`.

2. `pyKLIP` Astrometry and Photometry

`pyKLIP` measures planet position and flux in a process known as Bayesian KLIP Astrometry, or BKA (Pueyo 2016). In BKA, a forward model of the exoplanet is created and then fit to the data using a Bayesian analysis. This technique stems from the fact that in starlight subtraction, `pyKLIP` typically removes some planet light, thereby distorting its properties (Pueyo 2016; Wang et al. 2016). That distortion is due the planet's presence in the reference and/or science images, so if we can model the distortion features due to PSF subtraction, then finding a good fit of the model to our data can help us make more precise measurements of the planet's position and flux relative to its host star.

A better forward model of the planet increases the accuracy of our flux and position estimates, so it is essential that we are able to account for the effects of a coronagraph in this process. This means that if a planet located close to the star has 60% of its light blocked by the coronagraph, then we need to scale our flux measurements by the necessary amount to correct for this. Accomplishing this requires using the JWST published coronagraph transmission profiles to quantify the amount of light blocked at different separations from the host star.

We obtained simulated JWST/NIRcam data generated with the `pandeia-coronagraphy` package using recent measurements of telescope thermal stability (Perrin et al. 2018; Brooks et al. 2019). With this simulated data and NIRCam's coronagraphic transmission profiles, we added an optional argument to `pyKLIP`'s planet PSF forward modeling class that accepts a function to scale down the planet flux depending on its separation from the star. The usage of this feature is detailed on the `pyKLIP` documentation page.[4]

We tested the effectiveness of this coronagraphic correction by placing simulated planets into our data and using `pyKLIP` photometry to estimate their fluxes. Since we control the fluxes that we inject these fake planets at, we can easily quantify the accuracy of our `pyKLIP` flux estimates. For this test, we decided to use the NIRCam MASK210R coronagraph with simulated data taken through the F300M filter, a medium-bandwidth filter centered at 3.0 μm.

When we disabled our coronagraphic correction function, the `pyKLIP` estimates of planet flux were biased in the same way the coronagraph's transmission profile is biased (Figure 1). For example, at 7 pixels from the host star, the coronagraph is letting approximately 70% of light through. At this same pixel distance, we estimate the planet flux to be only 70% of what we actually injected it at. Between 20 pixels from the star ($1\overset{''}{.}26$) and 5 pixels from the star ($0\overset{''}{.}315$), the accuracy of our flux estimation went from 100% to approximately 60%. Conversely, enabling the correction function allowed us to estimate planet fluxes at close to 100% of what we injected them at regardless of the separation from the host star. Upon verification that this new function worked, we released it as part of `pyKLIP` v2.2

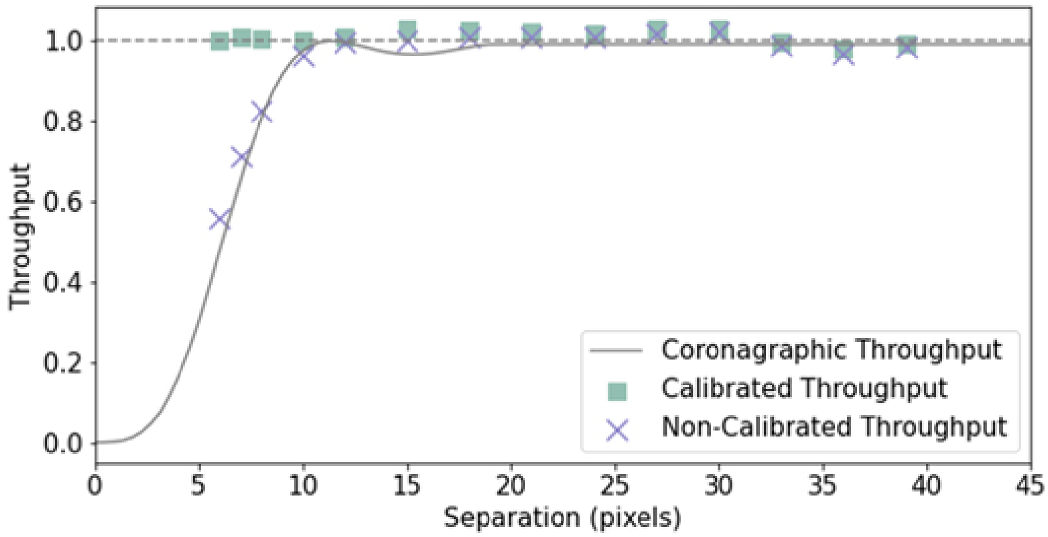

Figure 1. The accuracy of coronagraphic throughput correction. The solid black line indicates coronagraph's transmission profile. Purple x's represent the estimate of the flux of the planet when coronagraphic correction is turned off, while green squares show the estimate when the correction is enabled. When disabled, the flux estimate is biased in the same way that coronagraph's transmission profile is.

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3. Conclusion

This analysis served to improve the accuracy of photometry measurements made with JWST/NIRCam. Using simulated JWST data and NIRCam's coronagraphic transmission profiles, we highlighted the areas where photometry measurements are most affected by the use of coronagraphs. With alterations to the imaging software `pyKLIP`, we were able to correct for the use of NIRCam's coronagraphs, and verified that this correction was reliable at all planet–star separations. We have documented this throughput correction and created a tutorial to walk through its application in the ExoPix[5] package. This tutorial has been released along with a collection of other `pyKLIP` tutorials as part of a JWST Early Release Science Program.

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Footnotes

4 https://pyklip.readthedocs.io/en/latest/bka.html#correcting-for-coronagraphic-throughput

5 https://exopix.readthedocs.io/en/latest/